NIKER WORKSHOP
Tel Aviv, Israel 16.12.2012

STRENGTHENING INTERVENTIONS FOR VERTICAL AND HORIZONTAL ELEMENTS




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Dpt. of Civil, Environmental and Architectural Engineering

NEW INTEGRATED KNOWLEDGE BASED APPROACHES TO THE PROTECTION OF CULTURAL HERITAGE FROM EARTHQUAKE INDUCED RISK

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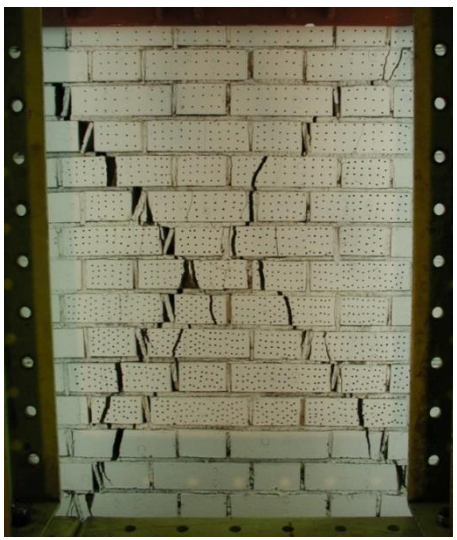
OPTIMIZATION OF DESIGN FOR VERTICAL ELEMENTS



Experimental campaigns carried out

Definition of:

- Adequate and feasible intervention methods for vertical structural elements

- Improvement of laboratory procedures for evaluating the intervention methods and specifications for laboratory specimens.

Masonry

Stone
hydraulic lime mortar
Regular and irregular blocks
UNIPD
NTUA
S&B
ENA

Clay brick
cement/earth mortar
Fired and unfired bricks
ITAM
ENA

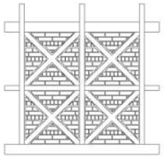
Earth block
earth mortar
mech. molded and CEBs
BAM
ITAM
ENA

Massive walls

Rammed earth
Compaction by hand
BAM

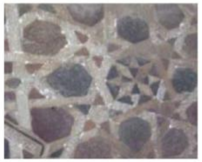
Cob
-
BAM

Composite



Timber
clay brick
cement mortar
-
UMINHO

Mosaics



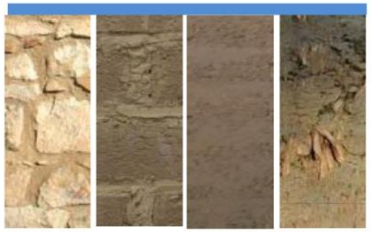
Ceramic, stone
hydraulic lime,
gypsum mortar
-
CDCU

Optimization of Design for vertical elements

- Characterize the experimental behaviour of original and strengthened walls, in order to obtain information on the system performance and the main constitutive laws relevant for modelling.

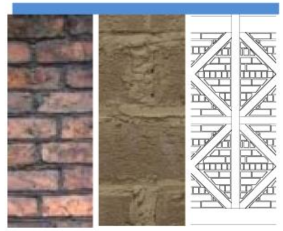
- Numerical simulation of the experimental behaviour and perform parametric assessment to define critical mechanical parameters or define optimized design procedures.

Grouting



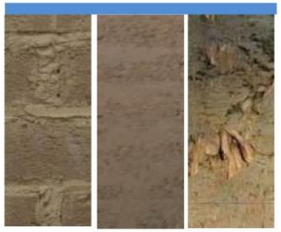
Lime based, earthen materials

FRP strips/Nets



GFRP, PP, PET

Textile belts



PE, 3 cm, 5 cm with hydraulic mortar

Others

Steel wire ropes

TESTING PROGRAMME

Material testing
- Grouting materials
- Mortars (lime, earth)
- Blocks (clay, earth)
- Cob, rammed earth

Wall element laboratory testing
- Masonry (stone, clay and earth block
- Massive walls (cob, rammed earth
- Timber frame

Cyclic tests
- In-plane shear
- Shear
- Shear bond
- Adhesion

Static tests
- Compression
- Shear
- Shear bond
- Adhesion

Wall in-situ testing
- Stone masonry

Static tests
- Diagonal shear test

Durability tests
- Grouting materials
- Reinforcement techniques (FRP)

TESTING PROGRAMME

Material group	Material	Testing	
		Partner	Experiment carried out
	**Stone masonry (non-grouted and grouted)**	UNIPD	Compressive strength In-plane cyclic shear test Diagonal compression/ shear strength
		NTUA	Compressive strength
	Stone masonry wall	ENA	
	**Half timbered walls**	UMINHO	Shear bond strength In-plane cyclic shear test

TESTING PROGRAMME

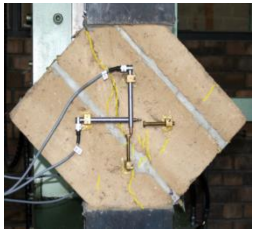
Material group	Material	Testing	
		Partner	Experiment carried out
	Clay bricks walls (unreinforced and reinforced)	ITAM	In-plane cyclic shear test
 	Earth block masonry		
	Rammed earth (unreinforced and reinforced)	BAM	Compressive strength Diagonal compression/ shear strength In-plane cyclic shear test
	Earth block masonry and cob (unreinforced)	BAM	Compressive strength Diagonal compression/ shear strength
	CEB masonry	ENA	Compressive strength

Optimization of Design for vertical elements

INTERVENTION TECHNIQUES

GROUT INJECTION OF STONE MASONRY WALLS (UNIPD & NTUA)

GROUT INJECTION OF EARTHEN WALLS (BAM)



TEXTILE BELTS OF EARTHEN WALLS (BAM)

GEOGRID AND STEEL WIRES FOR BRICK AND ADOBE WALLS (ITAM)

IMPROVED CONNECTIONS FOR HALF-TIMBERED WALLS (UMINHO)

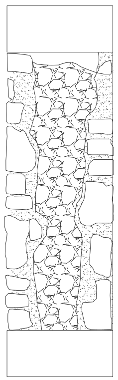
GROUT INJECTION OF STONE MASONRY WALLS (UNIPD)

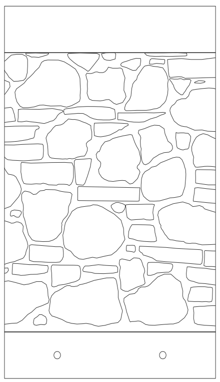
Monotonic and cyclic compression tests of three-leaf stone masonry walls

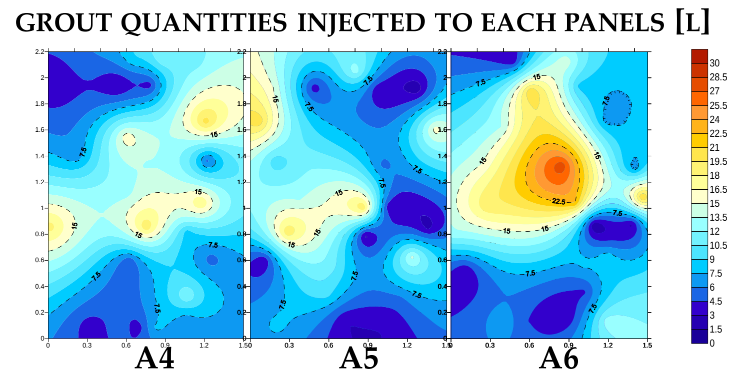
Monotonic tests									
Panel	**Scale**	**Condition**	**σ_{max} [N/mm^2]**	**$\sigma_{1,cr}$ [N/mm^2]**	**$\sigma_{1,cr}$ [%]**	**$E_{30\%-60\%}$ [N/mm^2]**	**$E_{10\%-40\%}$ [N/mm^2]**	**v_L [-]**	**v_T [-]**
B3	**1:1**	**UR**	2.1	0.4	21.0	1770	2885	0.044	0.030
B6		**R**	4.2	0.7	16.3	4421	4103	0.060	0.042
D2	**2:3**	**UR**	2.8	1.6	57.5	1364	2813	0.028	0.122
D4		**R**	5.4	4.4	81.0	3197	5030	0.013	0.020
F4	**Single-leaf (1:1)**	**UR**	6.5	1.2	18.9	1789	1691	*	-

GROUT INJECTION OF STONE MASONRY WALLS (UNIPD)

Monotonic and cyclic compression tests of three-leaf stone masonry walls





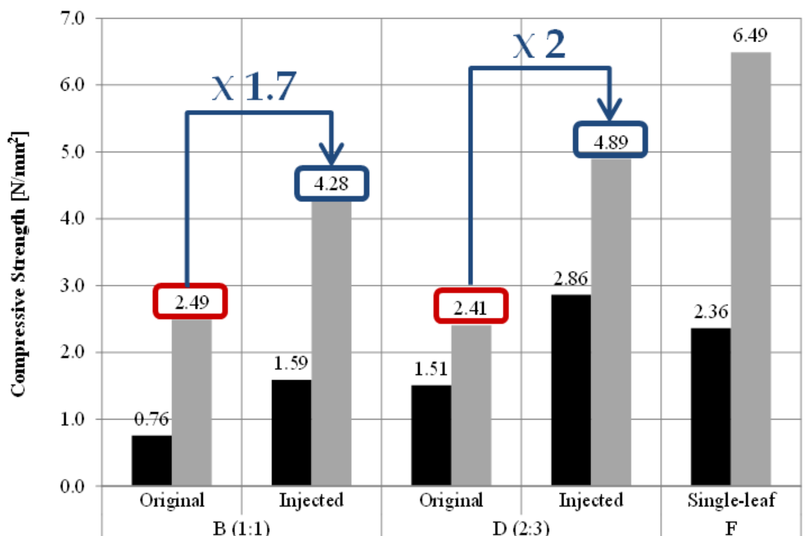


Cyclic tests

Panel	Scale	Condition	σ_{max} [N/mm²]	$\sigma_{1,cr}$ [N/mm²]	$\sigma_{1,cr}$ [%]	$E_{30\%-60\%}$ [N/mm²]	$E_{10\%-40\%}$ [N/mm²]	v_L [-]	v_T [-]
B1	**1:1**	**UR**	2.9	0.7	24	1487	2415	0.025	0.042
B2			2.5	1.1	46	1591	2294	0.069	0.061
B4		**R**	3.7	2.0	54	2404	4725	0.089	0.867
B5			4.9	2.1	43	3628	6781	0.003	0.288
D1	**2:3**	**UR**	2.2	1.4	64	3427	3427	0.010	0.122
D3			2.2	1.5	68	2033	2636	0.669	*
D5		**R**	4.0	2.7	66	3385	5708	0.012	0.123
D6			5.3	1.6	30	2810	4637	0.091	0.515
F1	**Single -leaf (1:1)**	**UR**	5.8	2.8	48	2536	3418	0.005	-
F2			6.7	2.6	39	2319	3486	0.008	-
F3			7.0	2.9	41	3681	4944	0.188	-

GROUT INJECTION OF STONE MASONRY WALLS (UNIPD)

Monotonic and cyclic compression tests of three-leaf stone masonry walls

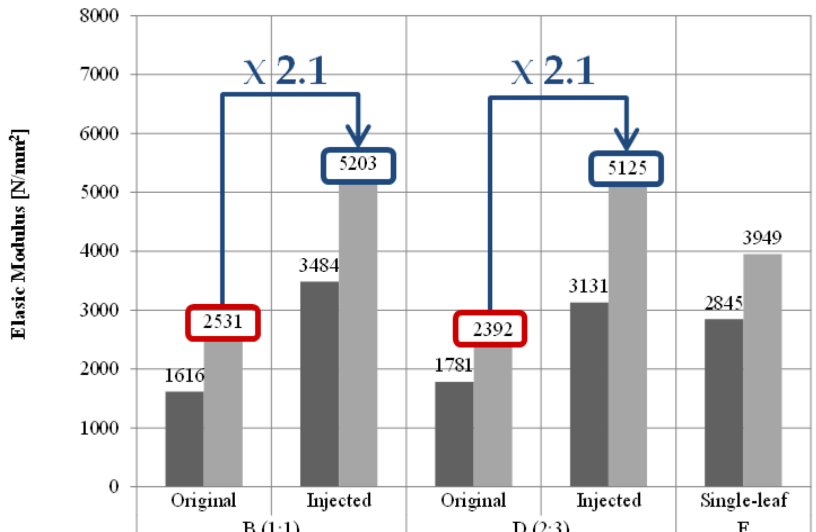


	B (1:1) Original	B (1:1) Injected	D (2:3) Original	D (2:3) Injected	Single-leaf F
σ1, cr,av [N/mm2]	0.76	1.59	1.51	2.86	2.36
σmax,av [N/mm2]	2.49	4.28	2.41	4.89	6.49

Increase of approximately 2 times of the compressive strength for both scales (slightly higher for the 2:3 scale specimens.

GROUT INJECTION OF STONE MASONRY WALLS (UNIPD)

Monotonic and cyclic compression tests of three-leaf stone masonry walls



	Original B (1:1)	Injected B (1:1)	Original D (2:3)	Injected D (2:3)	Single-leaf F
E 30%-60% [N/mm2]	1616	3484	1781	3131	2845
E 10%-40% [N/mm2]	2531	5203	2392	5125	3949

Increase of approximately 2 times of the compressive strength for both scales (slightly higher for the 2:3 scale specimens.

Optimization of Design for vertical elements

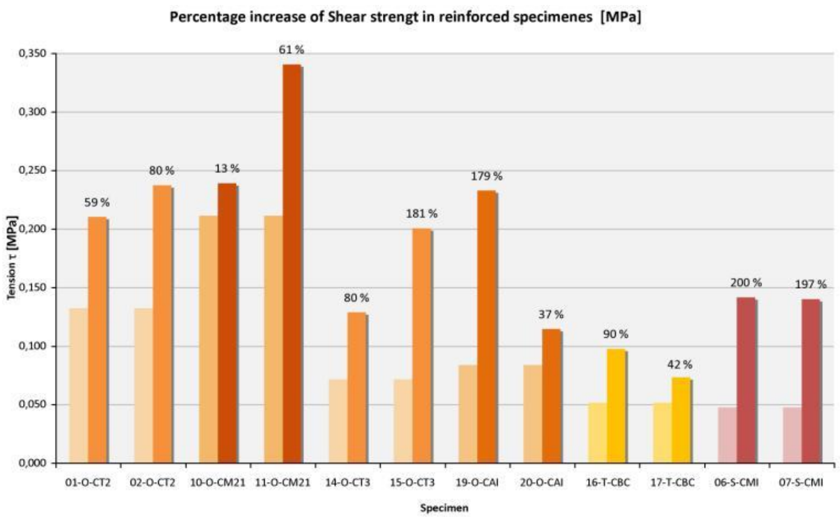
GROUT INJECTION OF STONE MASONRY WALLS ON SITE (UNIPD)

Monotonic and cyclic compression tests of three-leaf stone masonry walls

Increase Sonic velocity about 2,7 times

Increase Shear strength to 2 times

Increase Shear Modulus G to 5-10 times



Optimization of Design for vertical elements

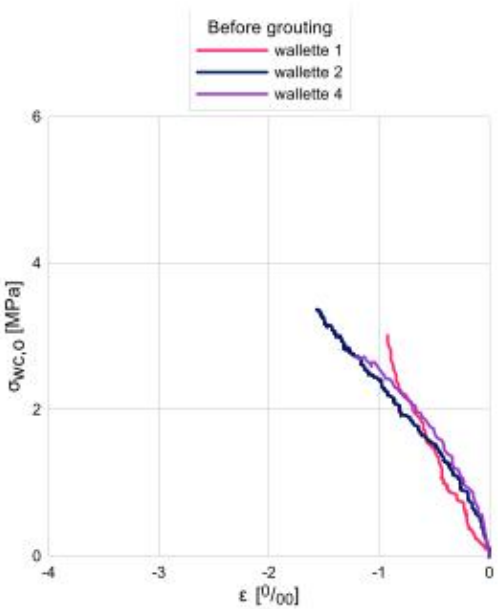
GROUT INJECTION OF STONE MASONRY WALLS (NTUA)

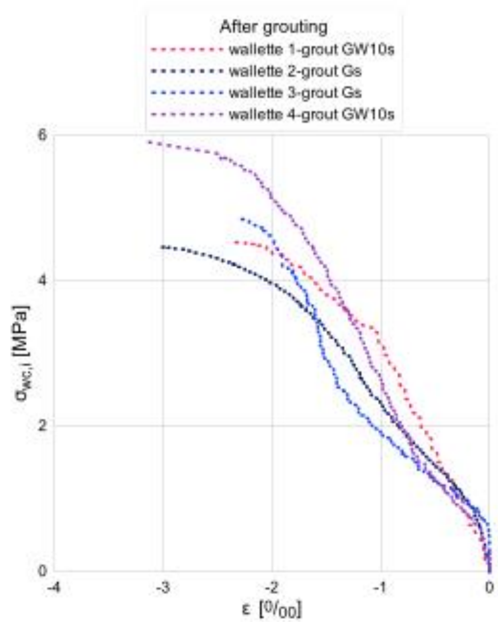
Compression tests

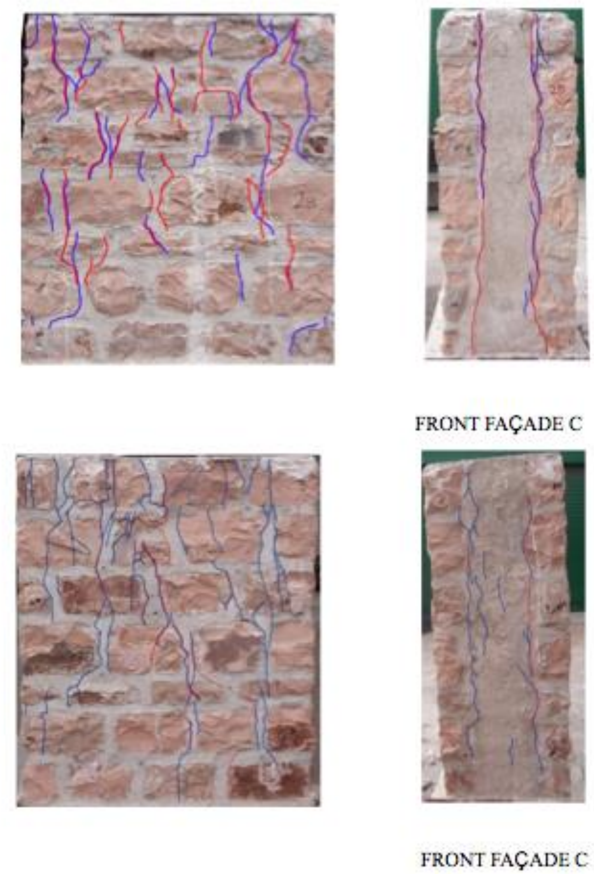
- **Scale:** 2:3, **Dimensions:** H=1.2 m, b=1.0 m, t=0.45 m
- **Percentage of voids (infill material):** ~40%
- **Measurements:** vertical, horizontal & transverse deformations

GROUT INJECTION OF STONE MASONRY WALLS (NTUA)

Compression tests





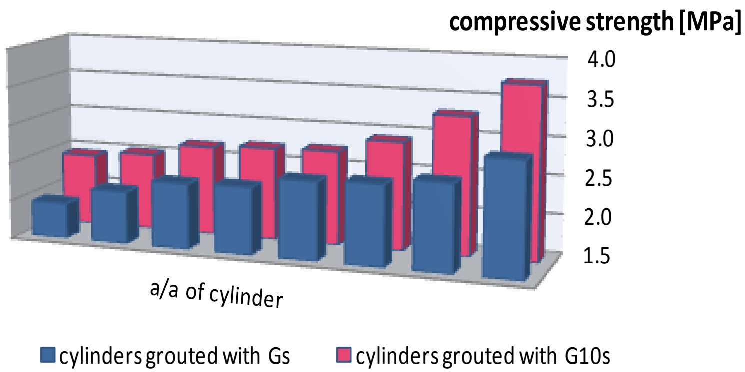


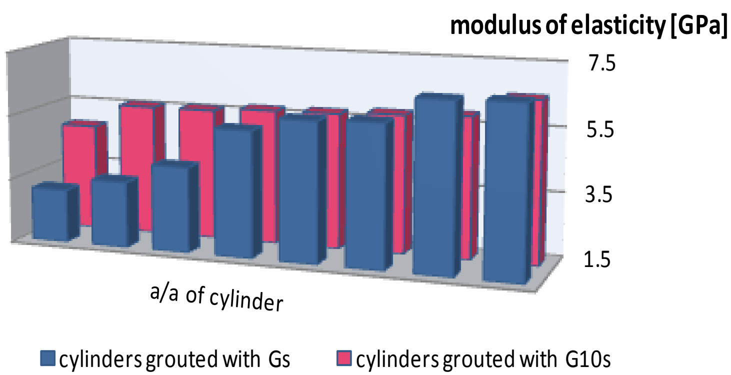
Failure mode in compression before (red line) and after (blue line) grouting of a) W. 2 and b) W. 4

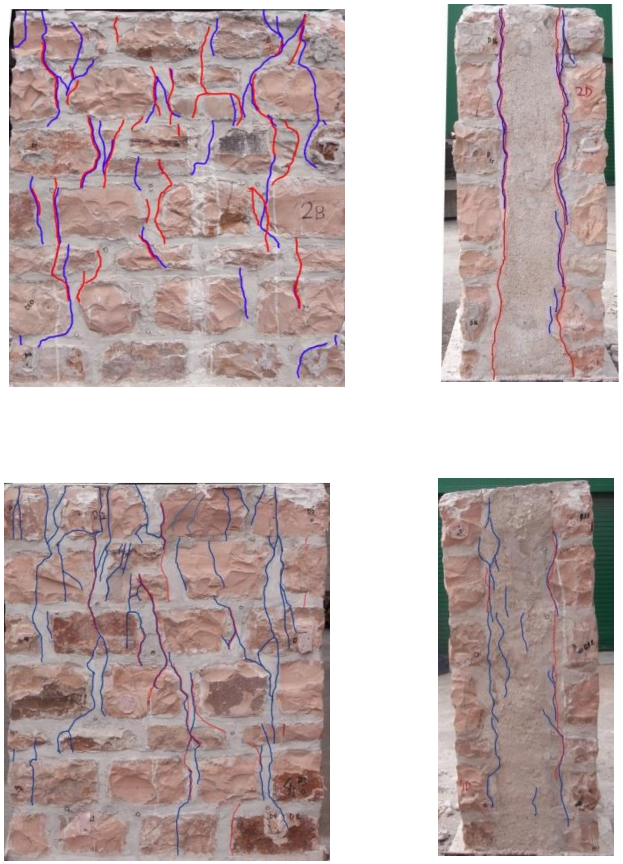
Optimization of Design for vertical elements

GROUT INJECTION OF STONE MASONRY WALLS (NTUA)

Compression tests



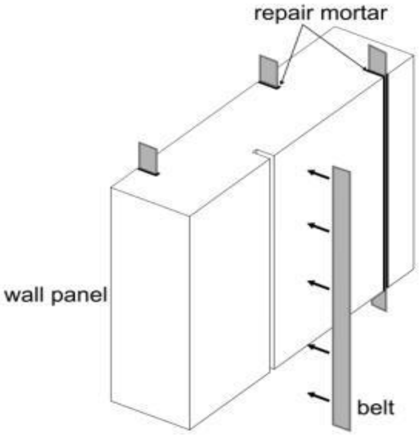


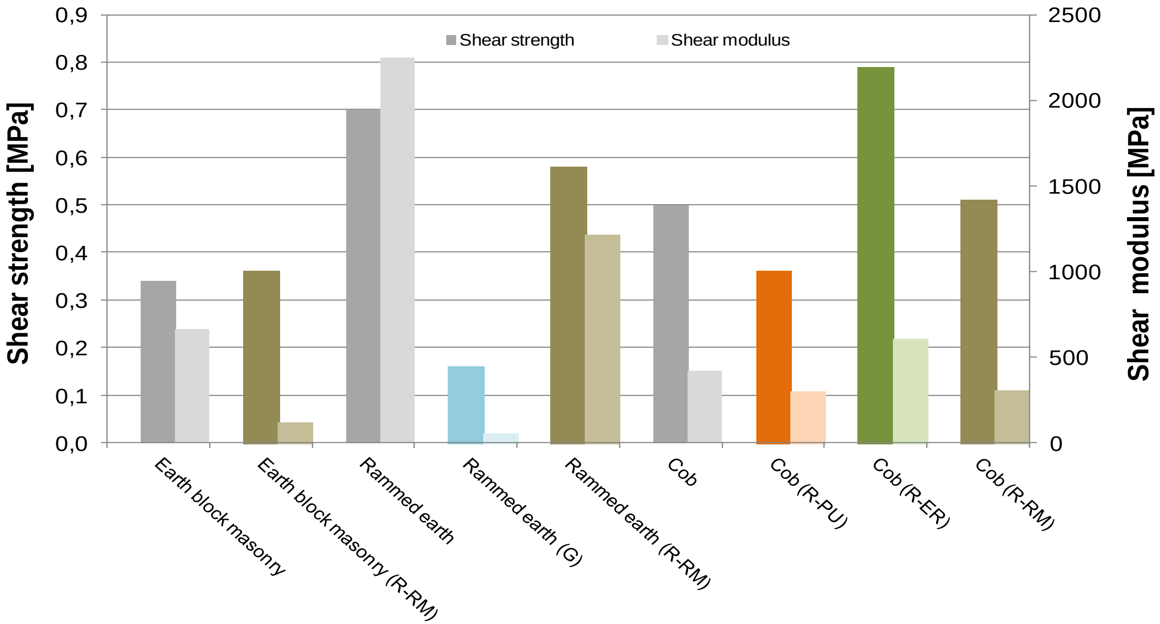


Failure mode in compression before (red line) and after (blue line) grouting of a) W. 2 and b) W. 4

GROUT INJECTION OF EARTHEN WALLS (BAM)

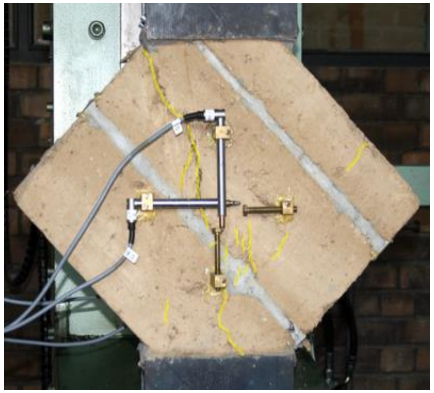
Diagonal compression tests





TEXTILE BELTS OF EARTHEN WALLS (BAM)

Diagonal compression tests

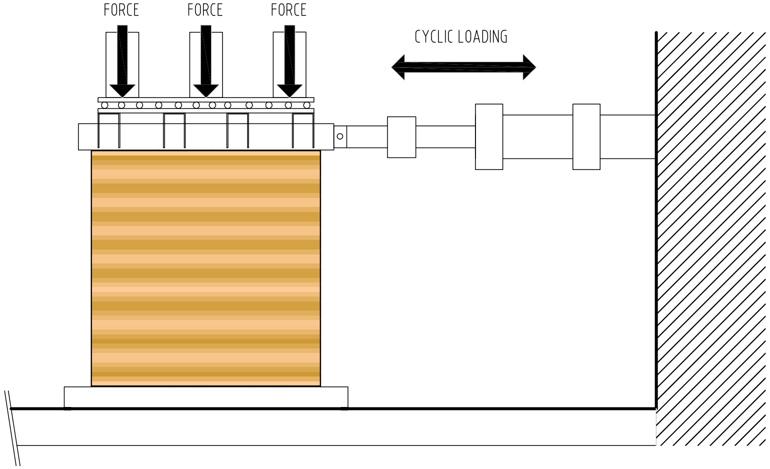



	Shear strength τ_u [MPa]		Shear modulus $G_{1/3}$ [MPa]		Shear strain $\gamma_{1/3}$ [%]	
	Mean	STD	Mean	STD	Mean	STD
Earth block masonry	0.34	0.06	660	246	0.020	0.011
Earth block masonry (R-RM)	0.36	0.08	120	124	0.192	0.170
Rammed earth	0.71	0.11	2326	710	0.011	0.003
Rammed earth (G)	0.16	-	52	-	0.105	-
Rammed earth (R-RM)	0.58	0.00	1211	347	0.017	0.005
Cob	0.50	0.10	420	137	0.041	0.006
Cob (R-PU)	0.36	-	301	-	0.040	-
Cob (R-ER)	0.79	-	608	-	0.043	-
Cob (R-RM)	0.51	0.06	306	99	0.058	0.012

TEXTILE BELTS OF EARTHEN WALLS (BAM)

In plane shear cyclic tests



Compressive loading: 140 kN. The vertical compressive pre-stress was combined with cyclic horizontal loading mode with a stepwise increase in the maximum cycling limits.

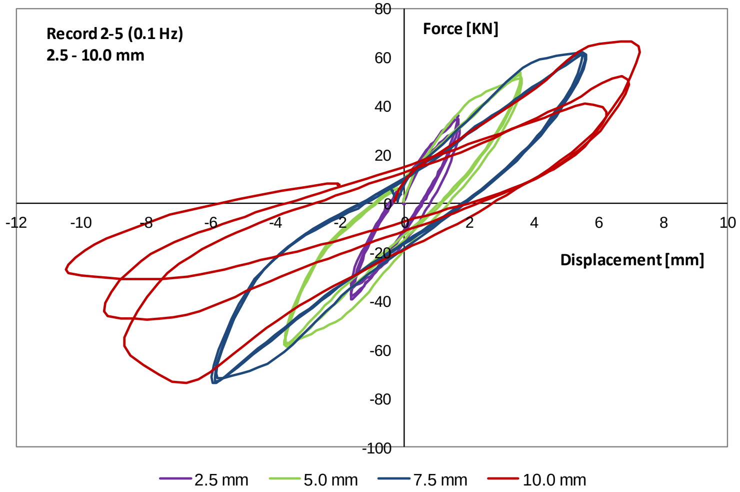
Scheme of the testing system

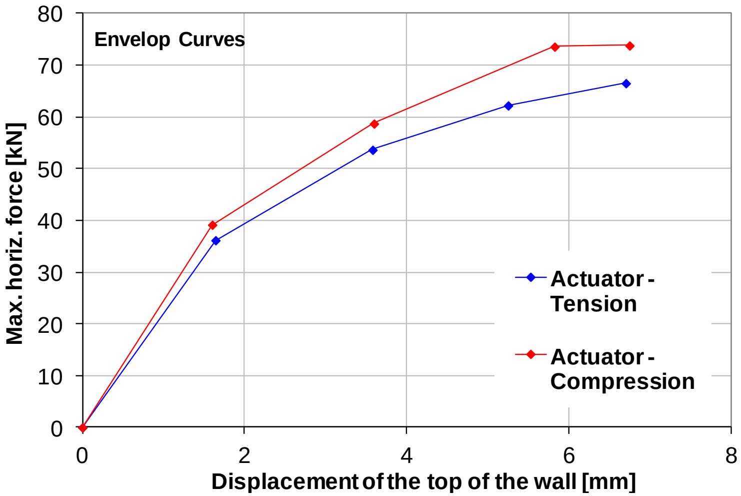
Tests performed at ITAM

Material	Retrofitting/reinforcement adopted	E [GPa]	Ø [mm]	Tensile strength
Rammed earth	Textile belts			Ca. 10 kN

TEXTILE BELTS OF EARTHEN WALLS (BAM)

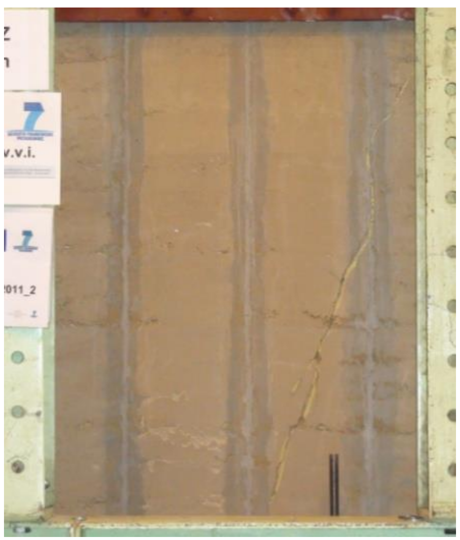
In plane shear cyclic tests: Unreinforced samples (REW)

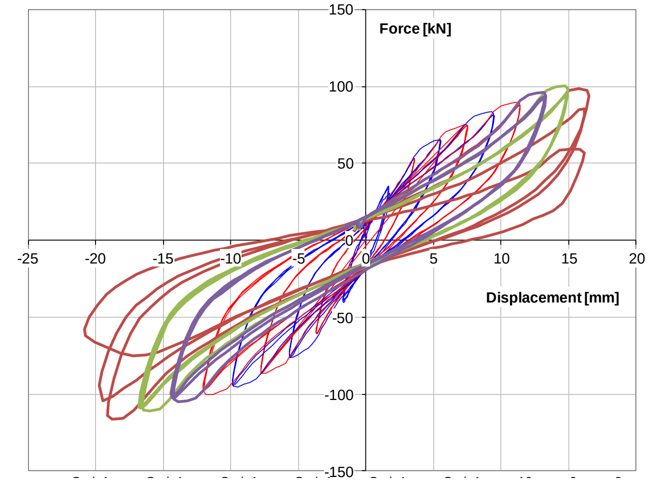


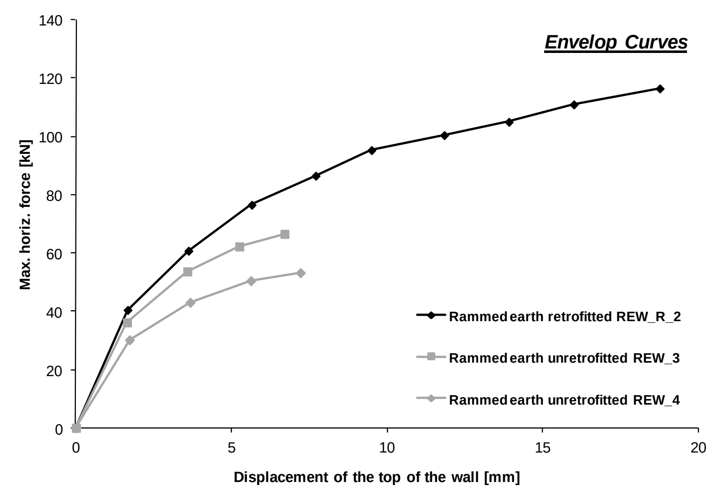


TEXTILE BELTS OF EARTHEN WALLS (BAM)

In plane shear cyclic tests: Reinforced samples (REW_R)





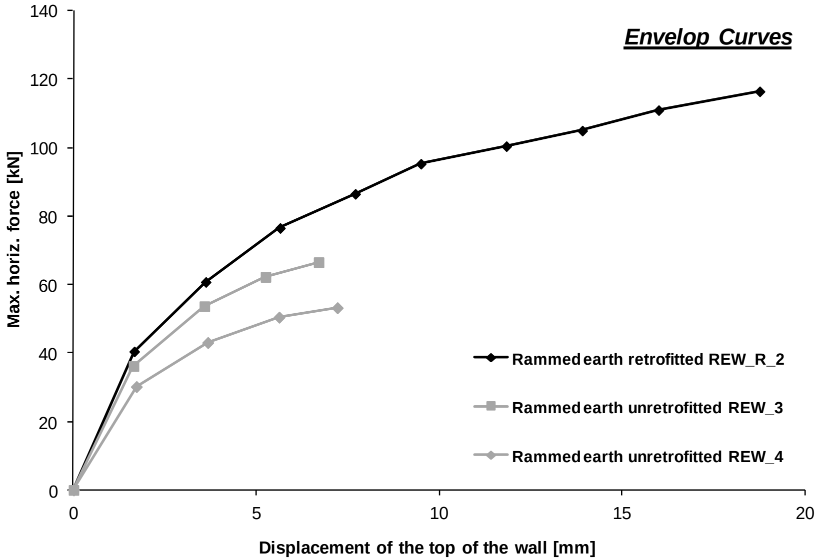


TEXTILE BELTS OF EARTHEN WALLS (BAM)

In plane shear cyclic tests: Comparison

Rammed earth walls by polyester textile belts: increase strain capacity of the walls under shear stress, without increase the stiffness of the wall.

Increase of the tolerance of the walls for horizontal forces and associated horizontal displacements.



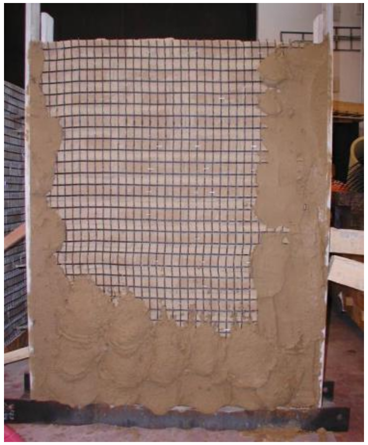
Specimen	Material	Vertical stress [MPa]	Horizontal load max [kN]	Failure mode
REW_3	Rammed earth	0.560	63	Shear
REW_4	Rammed earth	0.560	51	Shear
REW_R	Rammed earth	0.560	118	Shear/Flex

GEOGRID AND STEEL WIRES FOR BRICK AND ADOBE WALLS (ITAM)

In plane shear cyclic tests

Dry brick wall with geo-nets (DBW_3)

Solid brick wall with geo-nets (SBW_2)



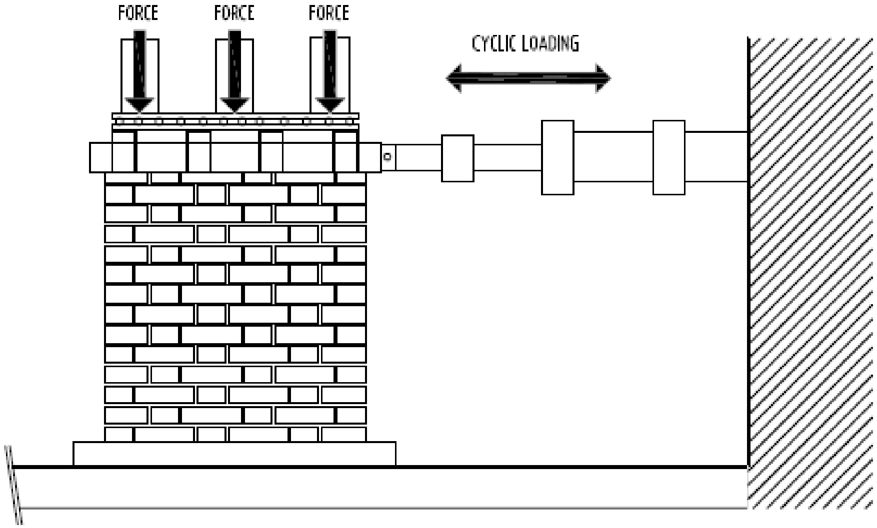
Adobe brick wall with geo-nets (ABW_3)

Adobe brick wall with a steel wire ropes (ABW_2)

Title	E [GPa]	Ø [mm]	Tensile strength	Mesh sizes [mm]
Wire ropes	210	4	1770 MPa	-
Geo-nets - polypropylene (PP) (TENAX)	-	-	9,3/17 kN/m	30 x 45
Geo-nets - polyester (PET) Miragrid GX 35/35(TENCATE)	-	-	35 kN/m (both directions)	25 x 25

GEOGRID AND STEEL WIRES FOR BRICK AND ADOBE WALLS (ITAM)

In plane shear cyclic tests



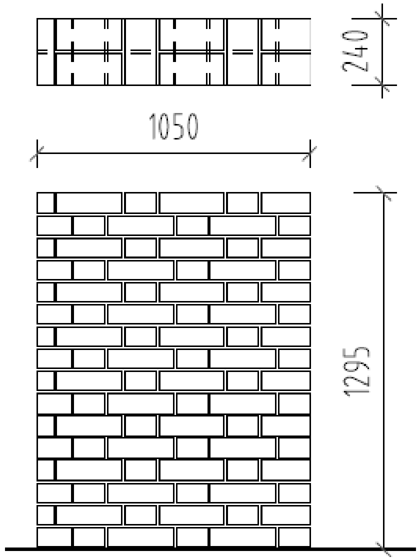
Scheme of the testing system

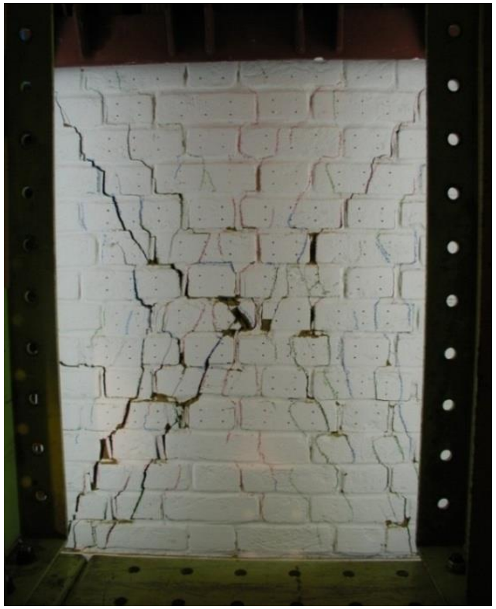
Compressive loading :80 kN. The vertical compressive pre-stress was combined with cyclic horizontal loading mode with a stepwise increase in the maximum cycling limits.

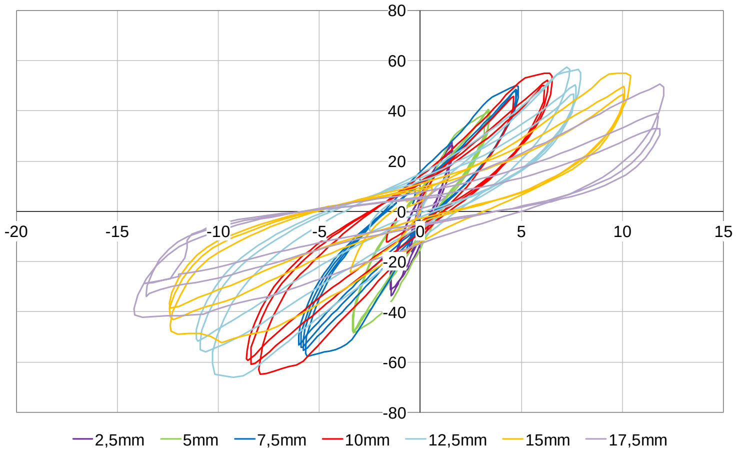
Optimization of Design for vertical elements

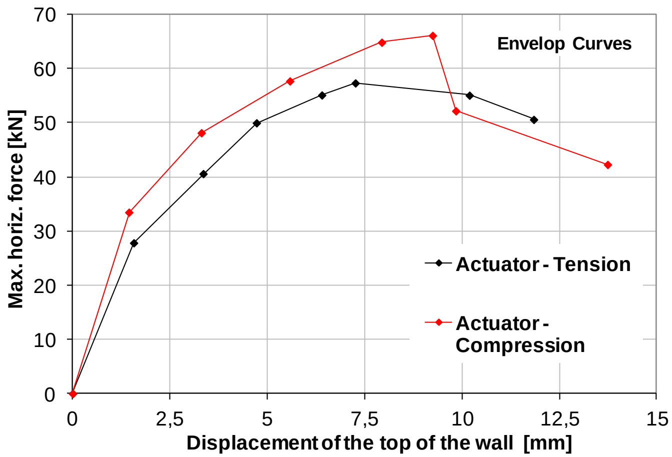
GEOGRID AND STEEL WIRES FOR BRICK AND ADOBE WALLS (ITAM)

In plane shear cyclic tests: Unreinforced samples (ABW_1)







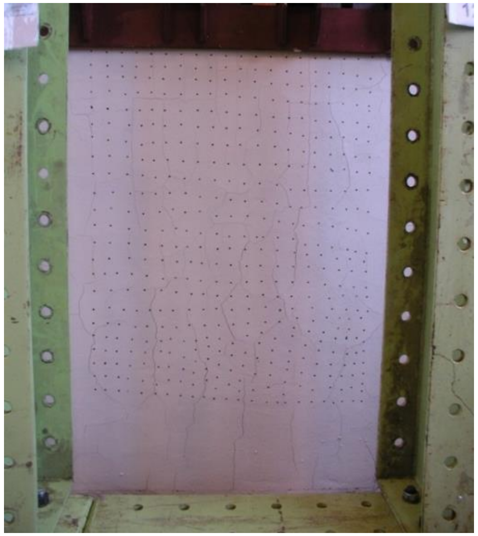


Typical failure cracking of a plain masonry wall without plaster loaded by combined uniformly distributed vertical static stress and a horizontal cyclic load.

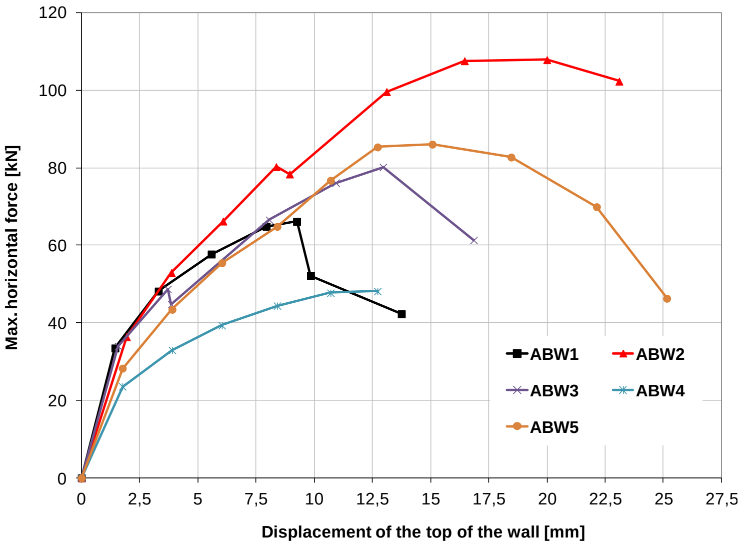
GEOGRID AND STEEL WIRES FOR BRICK AND ADOBE WALLS (ITAM)

In plane shear cyclic tests: Comparison

Reinforced samples with steel wire ropes (ABW_2)



Reinforced samples with PET geo-nets (ABW_3)



Specimen	Material	Vertical stress [MPa]	Horizontal load max [kN]	Failure mode
ABW_1	Earth block masonry	0.317	66	Shear
ABW_2	Earth block masonry	0.317	108	Shear/Flex-Rocking
ABW_3	Earth block masonry	0.317	80	Shear/Flex-Rocking
ABW_4	Earth block masonry	0.317	48	Shear/Flex-Rocking
ABW_5	Earth block masonry	0.317	85	Shear/Flex-Rocking

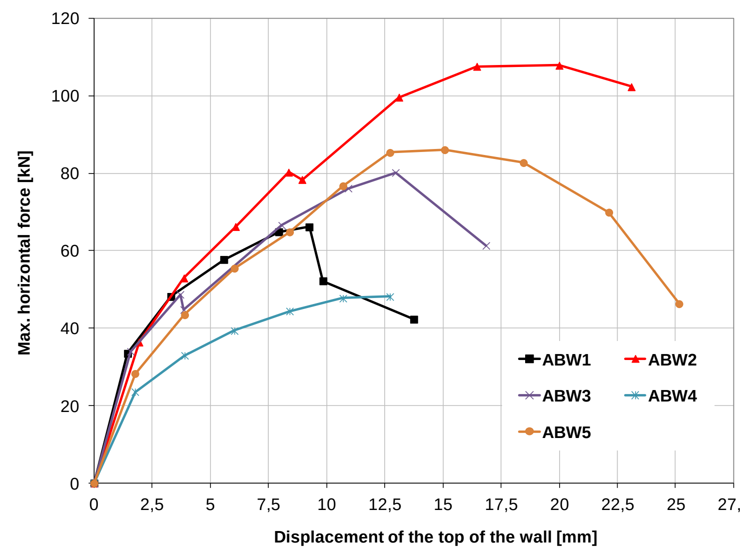
Optimization of Design for vertical elements

GEOGRID AND STEEL WIRES FOR BRICK AND ADOBE WALLS (ITAM)

In plane shear cyclic tests: Comparison

Retrof. samples (ABW_1) with geo-nets PET (ABW_4)

Reinforced samples with geo-nets PP (ABW_5)



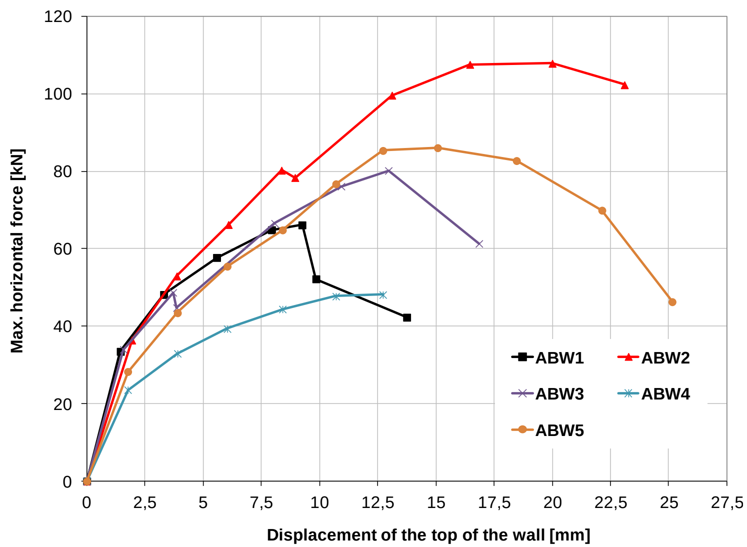
Specimen	Material	Vertical stress [MPa]	Horizontal load max [kN]	Failure mode
ABW_1	Earth block masonry	0.317	66	Shear
ABW_2	Earth block masonry	0.317	108	Shear/Flex-Rocking
ABW_3	Earth block masonry	0.317	80	Shear/Flex-Rocking
ABW_4	Earth block masonry	0.317	48	Shear/Flex-Rocking
ABW_5	Earth block masonry	0.317	85	Shear/Flex-Rocking

GEOGRID AND STEEL WIRES FOR BRICK AND ADOBE WALLS (ITAM)

In plane shear cyclic tests: Comparison

Retrofitted wall by means of geo-nets (PET) with the unreinforced adobe brick

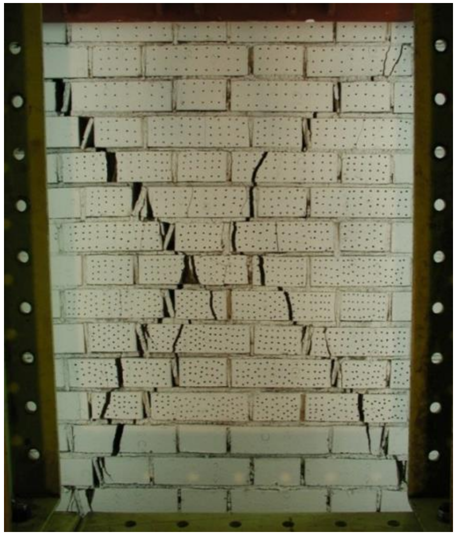
Strengthening with mortar reinforced with geo-net allow the specimen to reach strength of about 70% of the original situation.



Specimen	Material	Vertical stress [MPa]	Horizontal load max [kN]	Failure mode
ABW_1	Earth block masonry	0.317	66	Shear
ABW_2	Earth block masonry	0.317	108	Shear/Flex-Rocking
ABW_3	Earth block masonry	0.317	80	Shear/Flex-Rocking
ABW_4	Earth block masonry	0.317	48	Shear/Flex-Rocking
ABW_5	Earth block masonry	0.317	85	Shear/Flex-Rocking

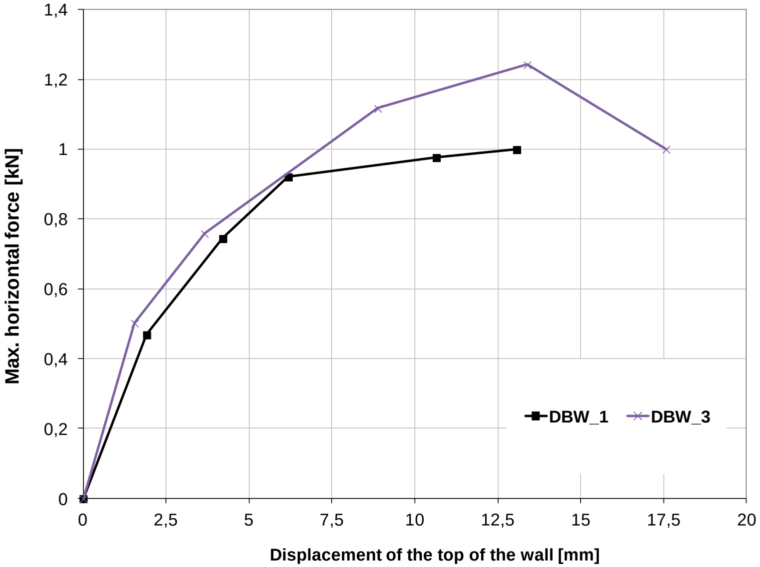
GEOGRID AND STEEL WIRES FOR BRICK AND ADOBE WALLS (ITAM)

In plane shear cyclic tests: Comparison



Dry brick wall unreinforced (DBW_1)

Dry brick wall with geo-nets (DBW_3)

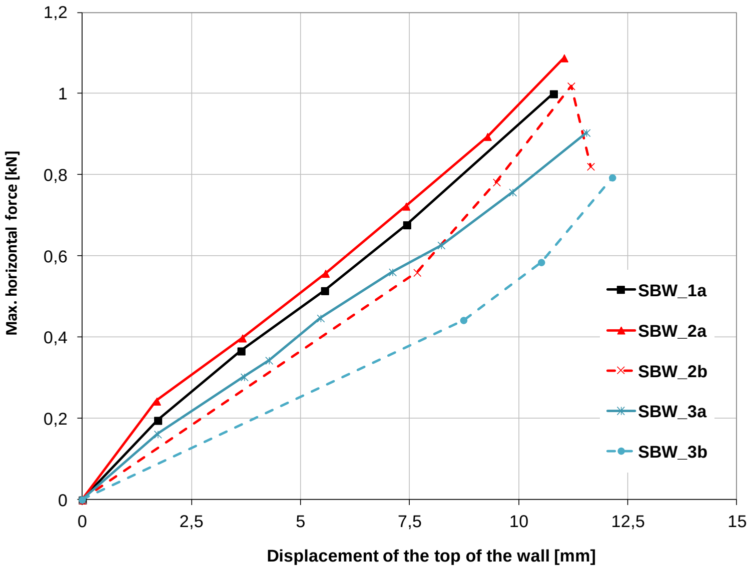


GEOGRID AND STEEL WIRES FOR BRICK AND ADOBE WALLS (ITAM)

In plane shear cyclic tests: Comparison

Solid brick wall unreinforced (SBW_1)

Solid brick wall with geo-nets (SBW_2)



GEOGRID AND STEEL WIRES FOR BRICK AND ADOBE WALLS (ITAM)

In plane shear cyclic tests: Conclusions

Reinforcements using wire ropes and geo-nets.
Increase of the strength and load-carrying capacity on cyclic horizontal loading.
steel ropes are a bit more effective than geo-nets.

Geo-nets provide compactness of the material of the wall even after the partial damage.

Further development

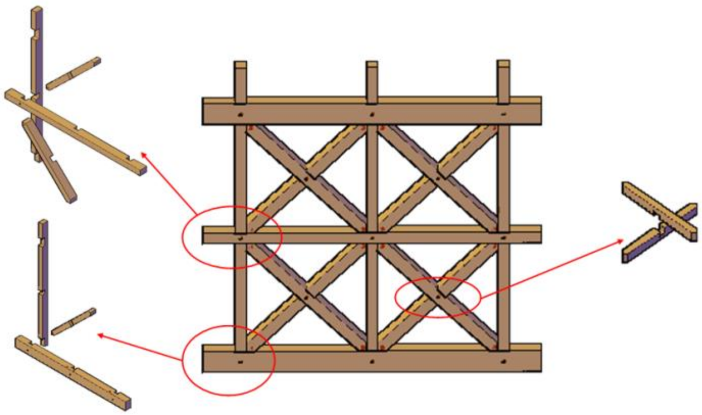
Investigate the bond behaviour between belt, adhesive and substrate.

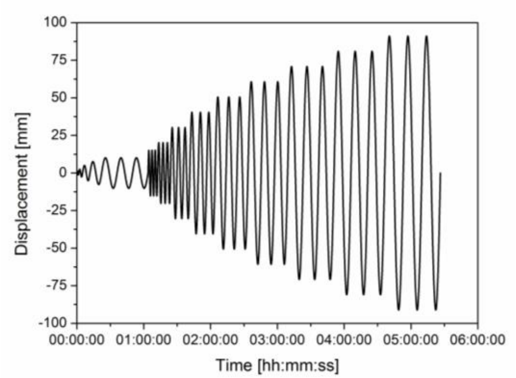
- Ration of width of belts
- Frequency of vertical belts per meter of wall length

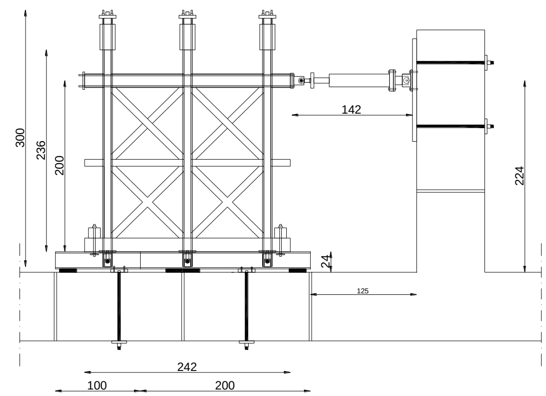
This has to be carried out by static pull-out tests as well as by cyclic tests on reinforced walls.

IMPROVED CONNECTIONS FOR HALF-TIMBERED WALLS (UMINHO)

In plane shear cyclic tests: unreinforced specimen







Unreinforced (UIW)

Unreinforced walls characterized by flexural behaviour, with posts uplifting → strengthening of connections to **prevent uplifting** and **improve shear behaviour**

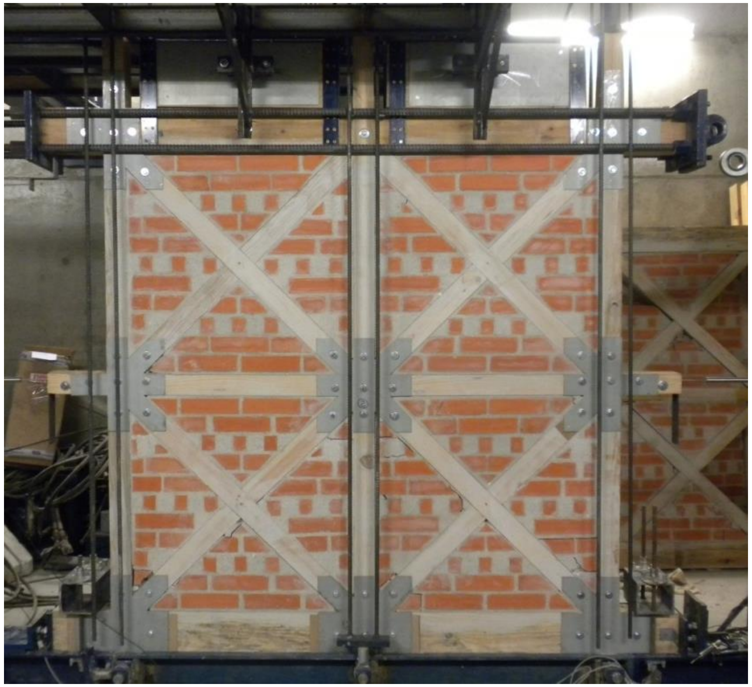
IMPROVED CONNECTIONS FOR HALF-TIMBERED WALLS (UMINHO)

In plane shear cyclic tests: strengthened specimens

Two types of strengthening: (1) bolts and (2) steel plates in all connections

Two vertical pre-compression levels: (1) 25kN/post and (2) 50kN/post

Bolts (RIW_B)



Steel plates (RIW_P)

Optimization of Design for vertical elements

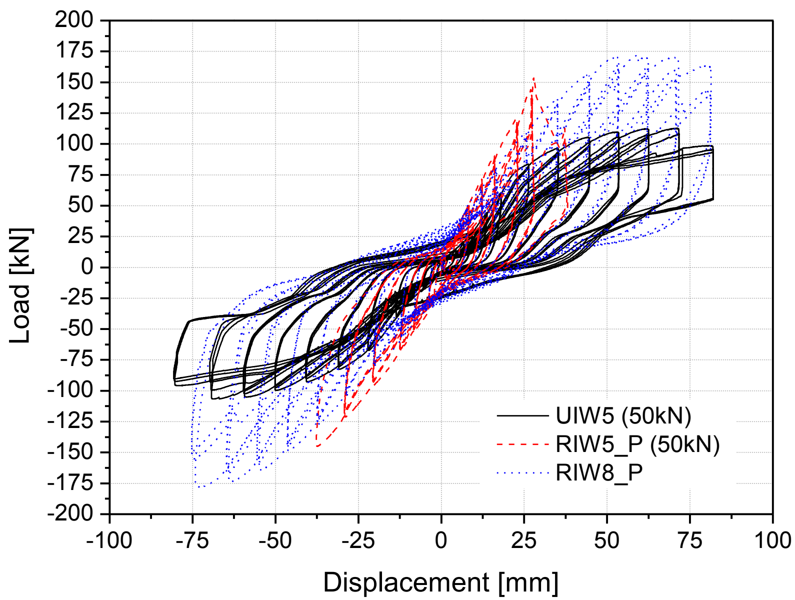
IMPROVED CONNECTIONS FOR HALF-TIMBERED WALLS (UMINHO)

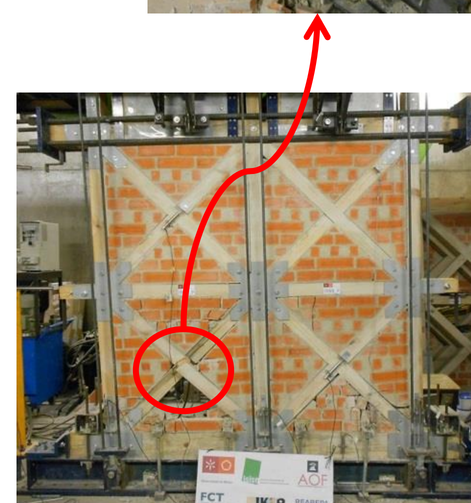
In plane shear cyclic tests: strengthened specimens

Two types of strengthening: (1) bolts and (2) steel plates in all connections

Two vertical pre-compression levels: (1) 25kN/post and (2) 50kN/pos

<u>Strengthening with steel plates</u>: vertical uplift prevented; wall gained significant stiffness, penalizing ductility. Diagonals were not able to work properly → rupture in diagonal connection





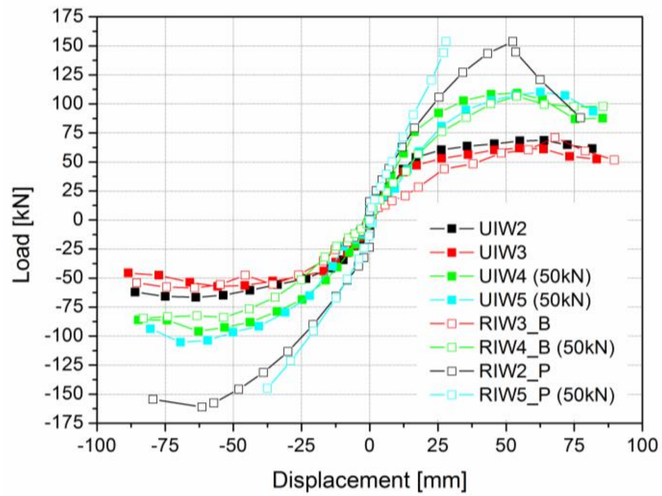
RIW_P

IMPROVED CONNECTIONS FOR HALF-TIMBERED WALLS (UMINHO)

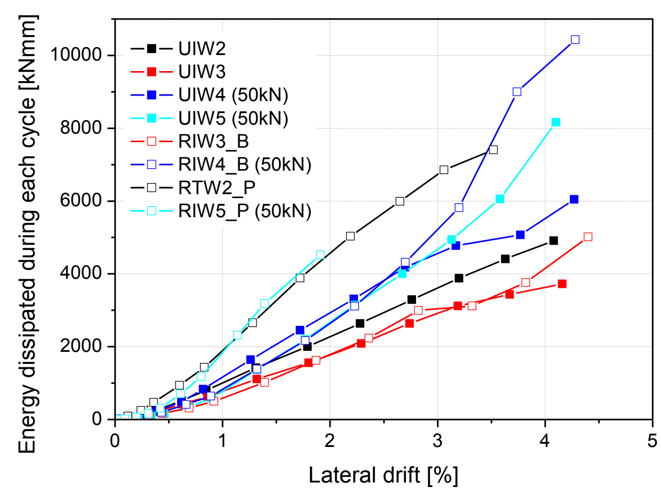
In plane shear cyclic tests: seismic parameters

RIW_B walls experienced a reduction in stiffness, but had better post-peak behaviour

RIW_P walls greatly stiffened the walls penalizing ductility



WALL	F_{max} [kN]	d_u [mm]	μ [-]	K [kN/mm]
UIW 25	64.54	82.31	4.46	3.69
UIW 50	112.79	83.67	2.89	3.56
RTW_B 25	78.61	87.97	2.54	2.14
RTW_B 50	107.00	86.00	2.07	2.48
RTW_P 25	153.69	78.27	1.62	6.01
RTW_P 50	173.21	77.12	1.55	5.63



CONCLUSIONS

The strengthening of walls needs to be focused on:

- Use of effective technological solutions
- Preservation of the original characteristics of the historical substrate

Strengthening interventions adopting traditional materials with traditional techniques and the use of innovative materials:

- Mechanical and chemical compatibility with existing materials, easy application and limited costs
- Durability and removability aspects can not be neglected

CONCLUSIONS

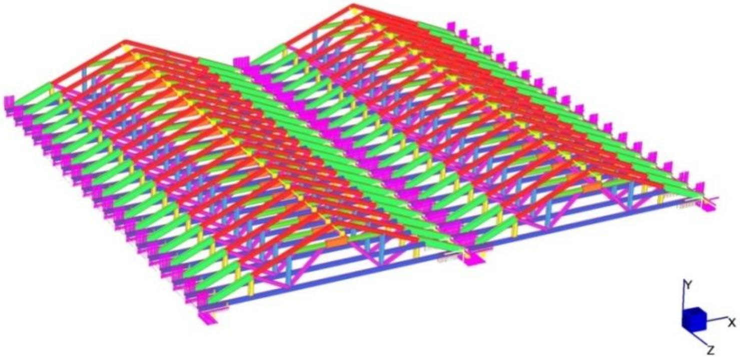
The techniques presented focused on the use of composite material and grouting, show an increase of:

- Load capacity
- Displacement capacity

The strengthening techniques adopted did not lead to the modification of the failure mode of structural elements tested.

They were efficient in improving significantly the compressive strength, as well as the deformability, without modifying the stiffness of structural elements.

OPTIMIZATION OF DESIGN FOR FLOORS, ROOFS AND VAULTS



Objectives

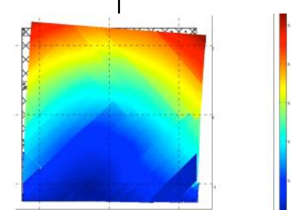
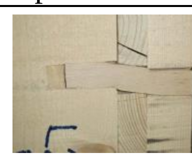
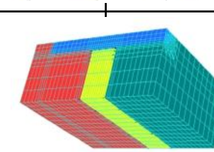
OPTIMIZATION OF DESIGN FOR FLOORS, ROOFS AND VAULTS

- Defining adequate and feasible intervention technologies for horizontal structural elements;
- Defining and improving laboratory procedures for evaluating the intervention technologies and specifications for laboratory specimens;
- Carrying out the necessary tests to characterize the experimental behaviour of original and strengthened wooden floors and roofs and masonry vaults, in order to obtain information on the system performance and the main constitutive laws relevant for modelling;
- Numerically simulating the experimental behaviour to perform parametric assessment and seek for structural limitations or define optimized design procedures



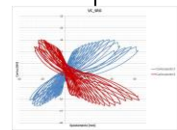
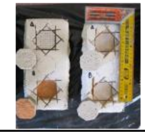
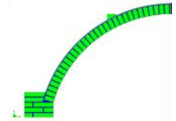
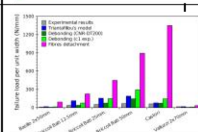
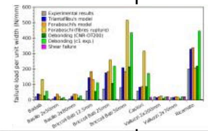
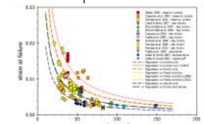
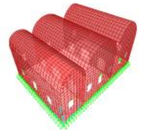
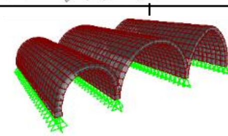
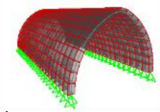
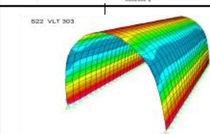
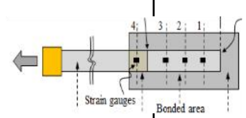
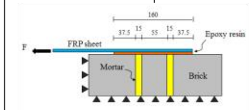
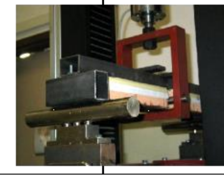

Optimization of Design for Floors, Roofs and Vaults

Research work on floors

FLOORS								
Level of investigation	Partner	Testing	Modeling			Parametric analysis		
		Experimental tests	Analytical modeling	FEM Linear	FEM Non Linear	Analytical modeling	FEM Linear	FEM Non Linear
Element	UNIPD BOZZA	Monotonic and cyclic tests on strengthened timber floors	Identification of in-plane stiffness and energy dissipation parameters	Calibration of global behaviour (in-plane strength and deformability)				
	ITAM	Experimental in-plane cyclic tests on authentic floor segments	Identification of in-plane stiffness and energy dissipation parameters	Calibration of global behaviour (in-plane strength and deformability)			Influence of planking orientation on the floor stiffness	
Local	UNIPD BOZZA			Characterization and calibration of behaviour of connections			Influence of connections on the global behaviour of floors	

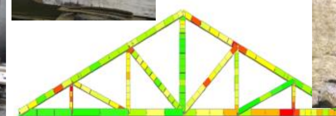
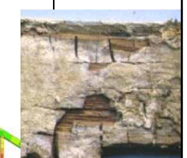
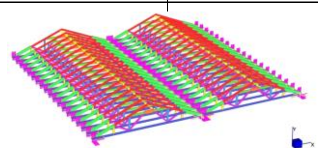
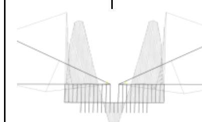
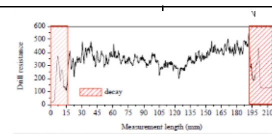
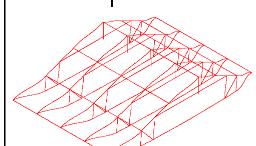
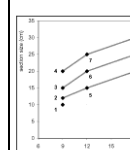
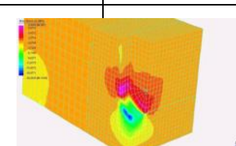
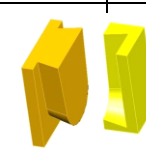
Optimization of Design for Floors, Roofs and Vaults

Research work on vaults

VAULTS								
Level of investigation	Partner	Testing	Modeling			Parametric analysis		
		Experimental tests	Analytical modeling	FEM Linear	FEM Non Linear	Analytical modeling	FEM Linear	FEM Non Linear
Element	UNIPD	Monotonic and cyclic tests on barrel vaults						
	UBATH	Pseudo-dynamic and cyclic tests on arches						
	UPC				Modelling of strengthened vaults			Simulation of strengthening and failure modes
	UNIPD					Calibration of design parameters for shear bond		
	GUNI					Interaction of parallel vaults with boundary conditions		
Local	UMINHO	Shear bond of composites to brick units			Shear bond behaviour between bricks and composites			3D modelling of bond behaviour on prisms
	UNIPD	Bond of composites (pull-off, shear loads, dowel effect) to bricks	Analytical formulation of local mechanisms in strengthened conditions			Influence of local effects on load capacity. Calibration of pull-off bond		

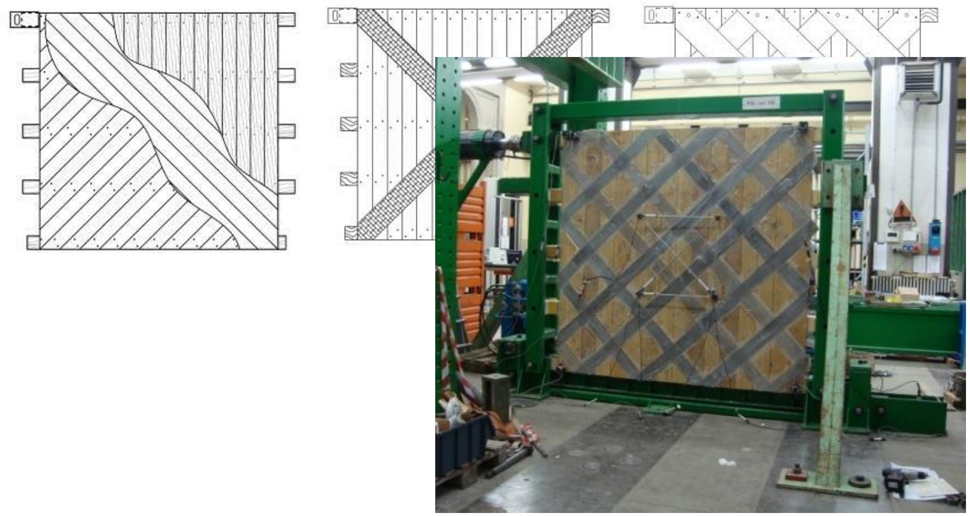
Optimization of Design for Floors, Roofs and Vaults

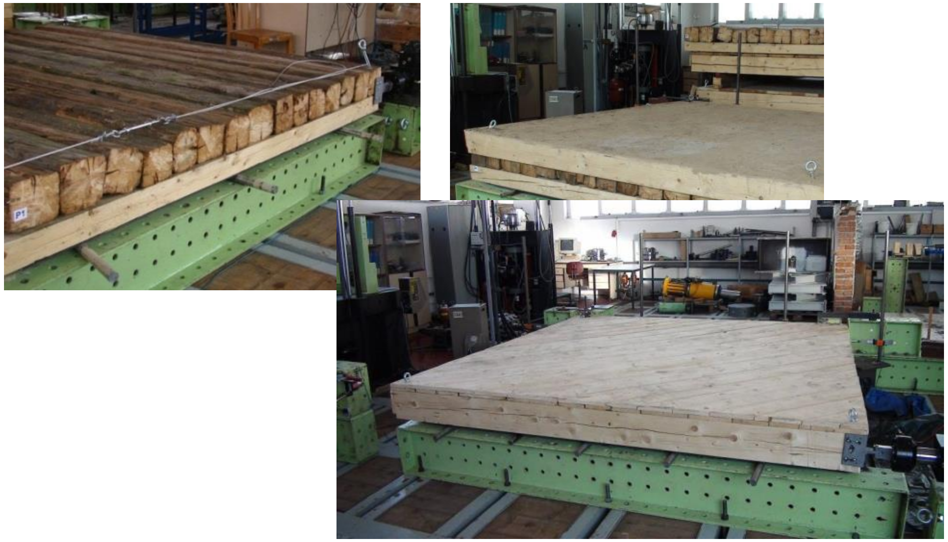
Research work on roofs

ROOFS								
		Testing	Modeling			Parametric analysis		
Level of investigation	Partner	Experimental tests	Analytical modeling	FEM Linear	FEM Non Linear	Analytical modeling	FEM Linear	FEM Non Linear
Element	UMINHO	Vertical loading on wooden trusses rescued from existing building and deterioration investigation on connections						
	ENA	Physical and mechanical characterization of wooden materials in timber elements	Verification of wooden floors and joists based on design criteria					
	UNIPD			Modelling of series of trusses				Influence of corbel length on behaviour of serial trusses
	UMINHO			Modelling the load-carrying tests performed in full-scale timber trusses		Reliability assessment of timber trusses from NDT data		
	POLIMI			Dynamic response of roof structures			Influence of geometric parameters in seismic vulnerability of timber trusses	
Local	UNIPD BOZZA			Calibration of mortise-tenon joint behaviour				

Experimental results and analyses on floors

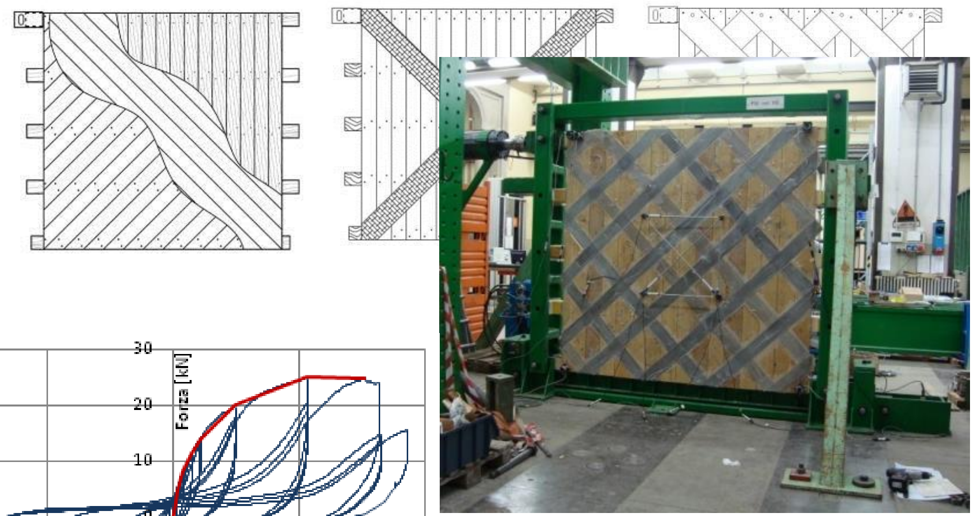
- Different strenghetning systems (plankings, diagonals, nets, ..) and materials (wood, earth, FRP, Natural fibres) applied at the extrados, for a total of 35 laboratory tests

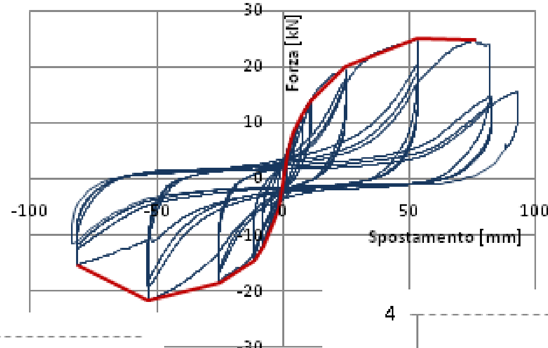


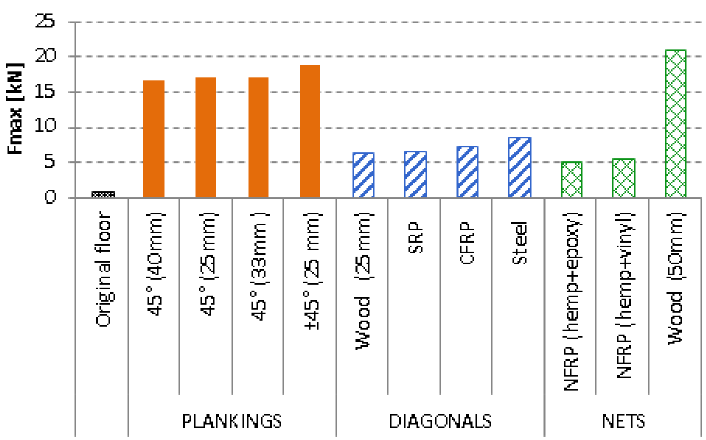


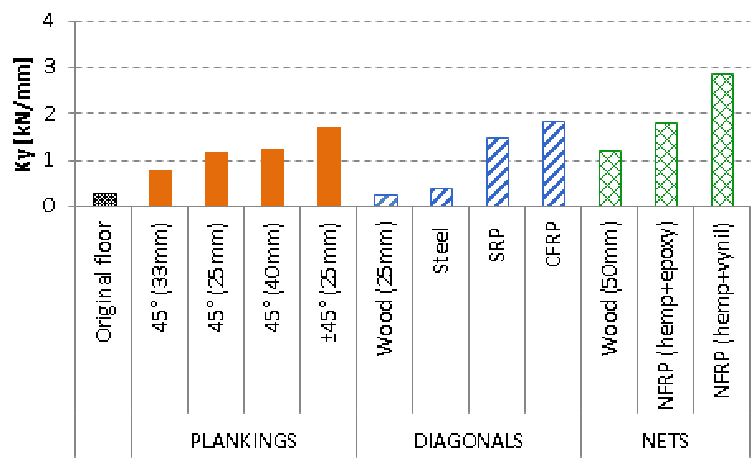
Experimental results and analyses on floors

- Different strenghetning systems (plankings, diagonals, nets, ..) and materials (wood, earth, FRP, Natural fibres) applied at the extrados, for a total of 35 laboratory tests
- High performance obtained for wooden planking (45° , single or double) both for strength and deformation capacity









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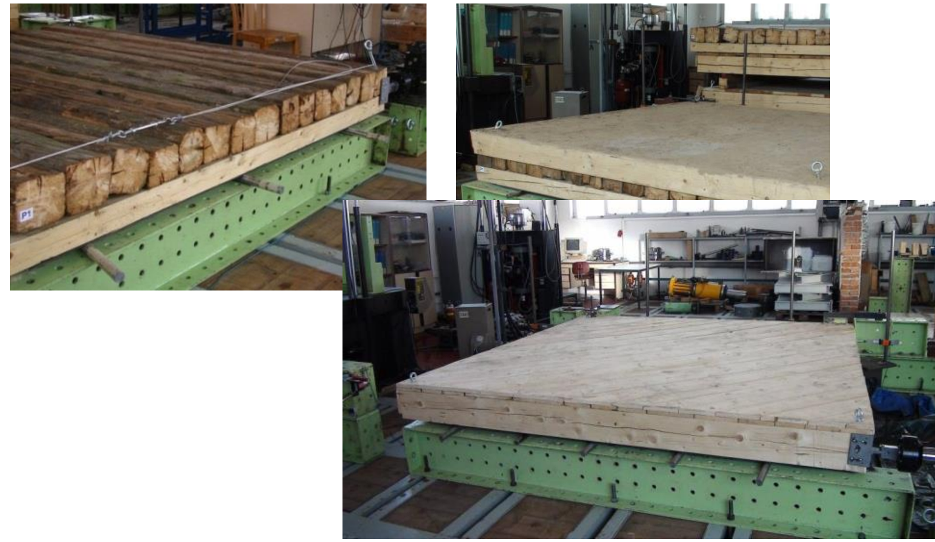
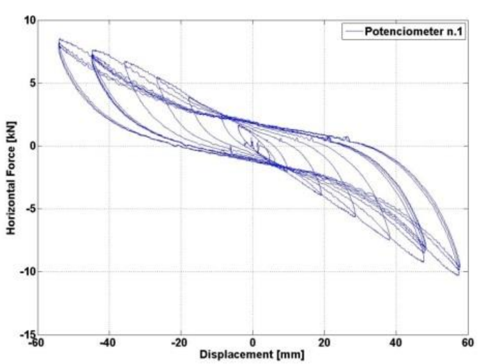
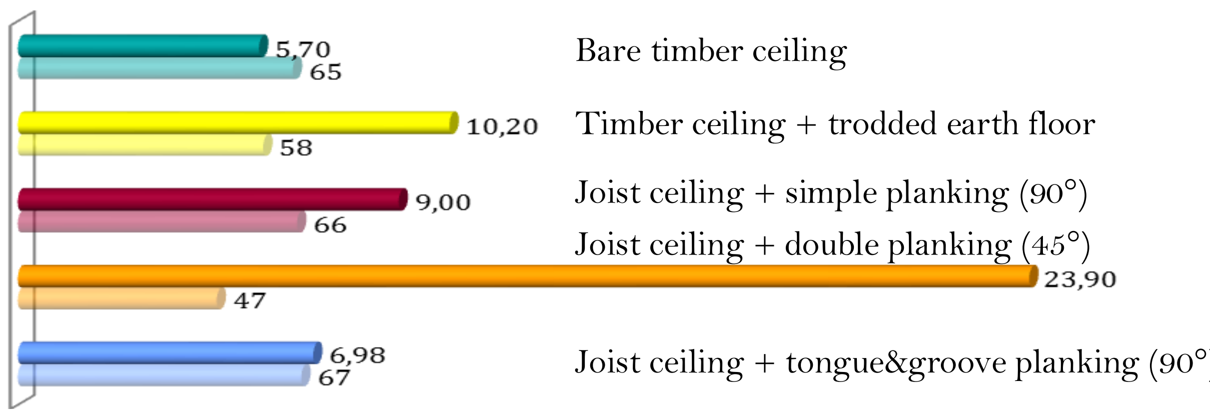


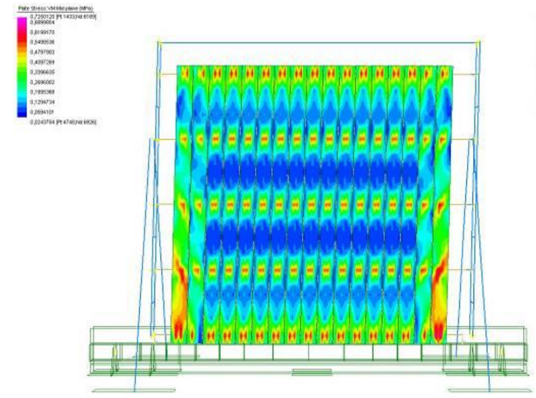


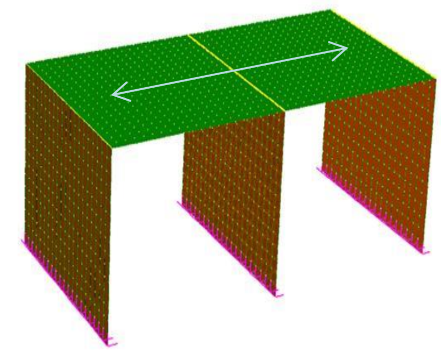


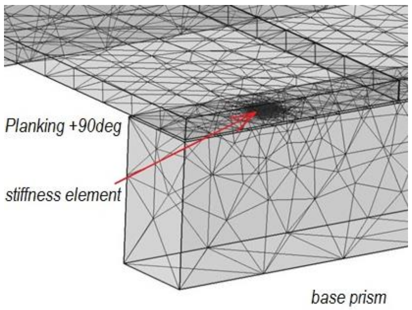
Optimization of Design for Floors, Roofs and Vaults

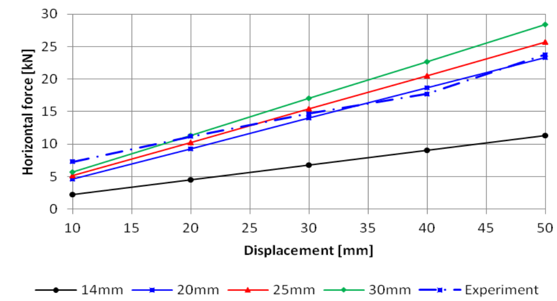
Experimental results and analyses on floors

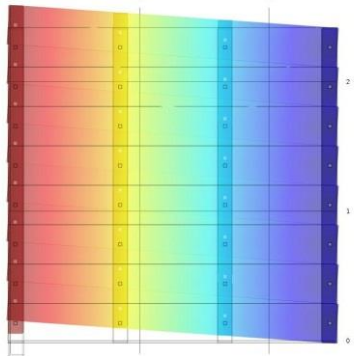
- Different strenghetning systems (plankings, diagonals, nets, ..) and materials (wood, earth, FRP, Natural fibres) applied at the extrados, for a total of 35 laboratory tests
- High performance obtained for wooden planking (45°, single or double) both for strength and deformation capacity
- The shear stiffness of the joist ceiling is principally influenced by the planking thickness
- The shear capacity of the floors is linearly related with the strength of the fasteners
- Proper double planking provides stiffness capable to redistribute horizontal loads to bearing walls, comparable to the effect of more modern floors

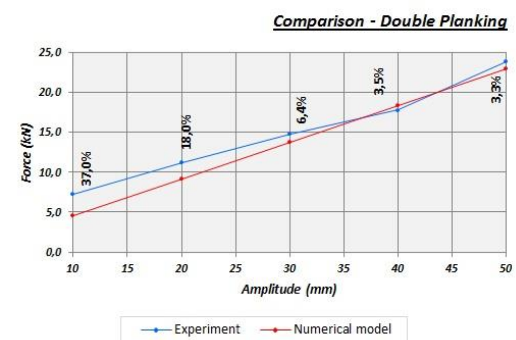












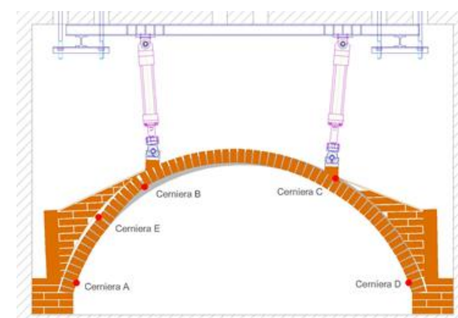
Experimental results and analyses on vaults

- Main technique: use of composites (FRP, SRP/G, TRM) applied at the extrados or at the intrados or to stabilize transverse walls (alternative technique) in 11 configurations
- Extrados strengthening is more effective than intrados (higher load capacity and less brittle failure)







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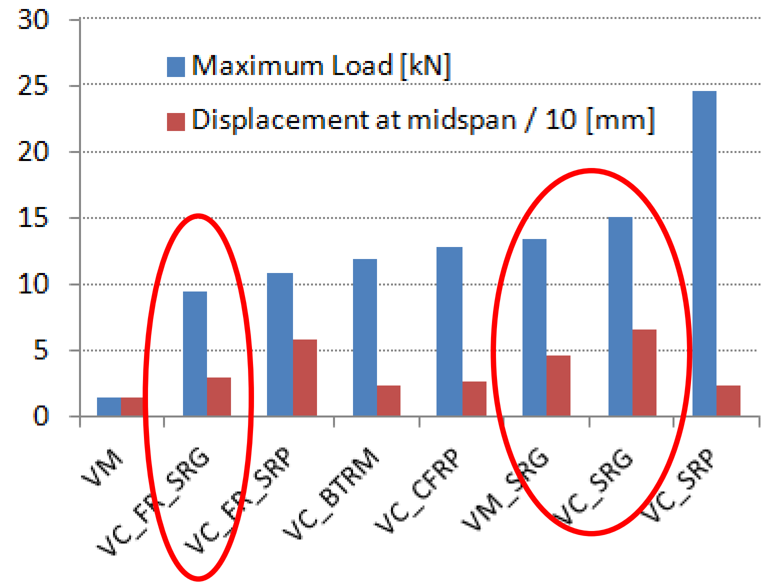
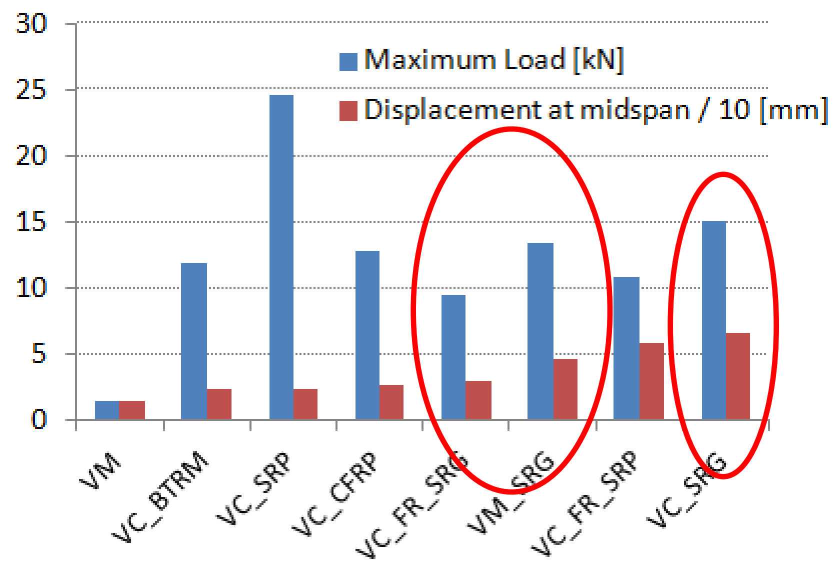
- Use of inorganic mortars allows larger displacements than epoxy (4 times higher than the unstrengthened vaults vs. 1.5 for epoxy) and sufficiently high load capacity (10 times more than plain vaults vs. 17 for epoxy)

	Results			
	Maximum Load	F_i/F_{VM}	Displacement at midspan	d_i/d_{VM}
Specimen	kN		mm	
VM	1,39	1,00	15,146	1,00
VC_FR_SRG	9,43	6,77	30,425	2,01
VC_FR_SRP	10,84	7,79	58,960	3,89
VC_BTRM	11,85	8,52	23,088	1,52
VC_CFRP	12,77	9,18	26,359	1,74
VM_SRG	13,37	9,61	46,983	3,10
VC_SRG	15,12	10,87	65,466	4,32
VC_SRP	24,69	17,74	23,758	1,57





Experimental results and analyses on vaults

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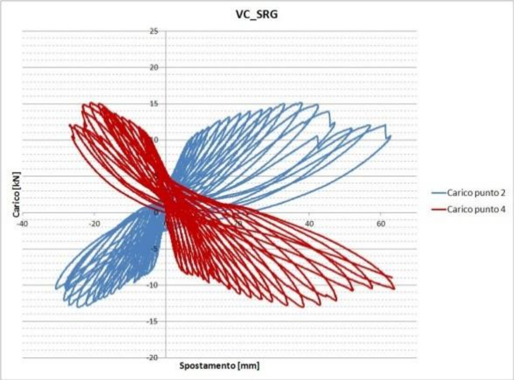
- Use of anchors (spikes) is fundamental to prevent shear sliding (brittle mechanism) at the base of the vault



Optimization of Design for Floors, Roofs and Vaults

Experimental results and analyses on vaults

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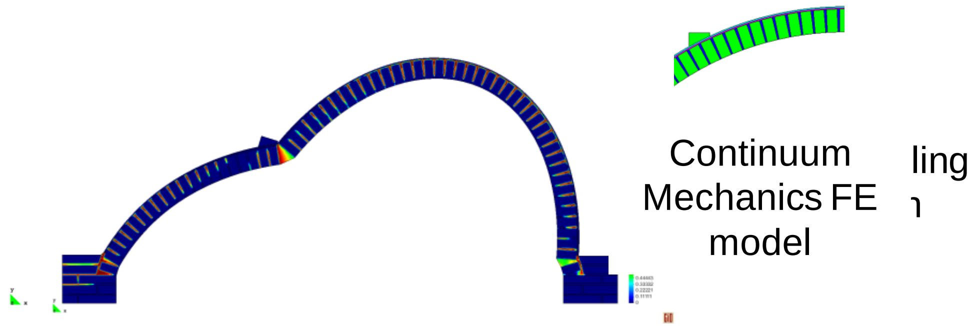
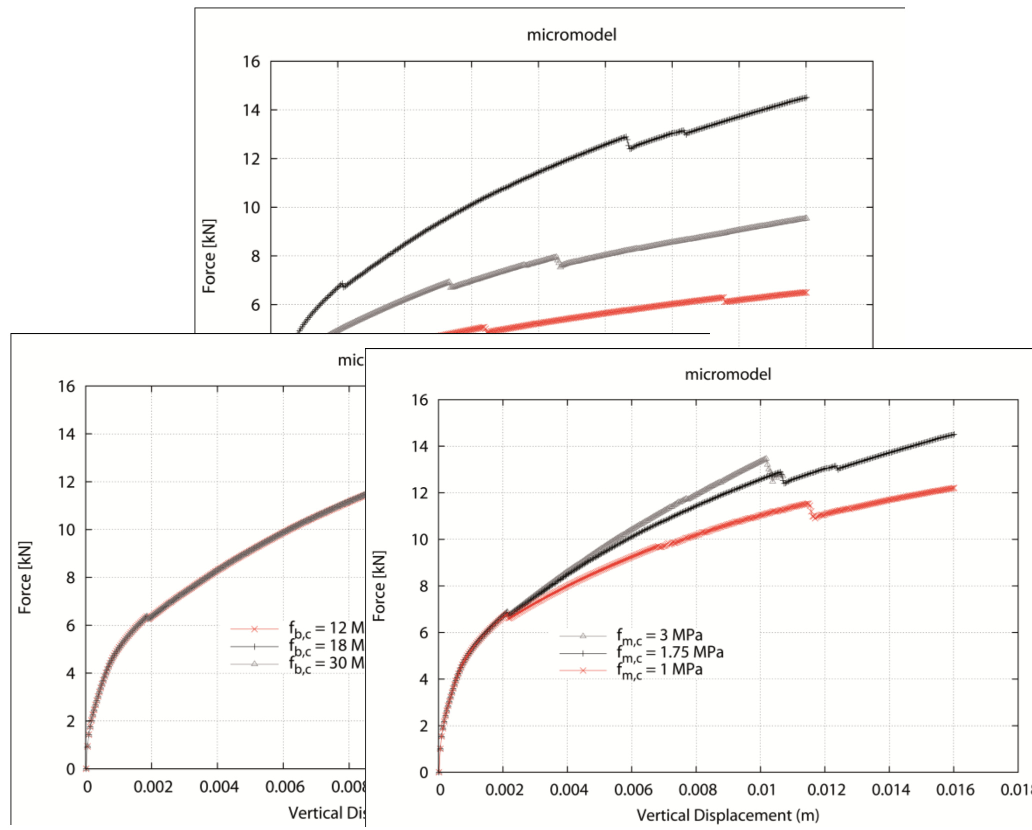
- Use of anchors (spikes) is fundamental to prevent shear sliding (brittle mechanism) at the base of the vault
- Compressive strength of mortar influence the vault capacity more than the brick one, although high strength mortars are not recommended to be used, as they may lead to a reduced displacement capacity in the nonlinear range

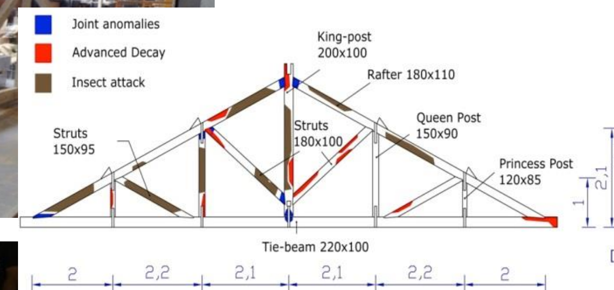


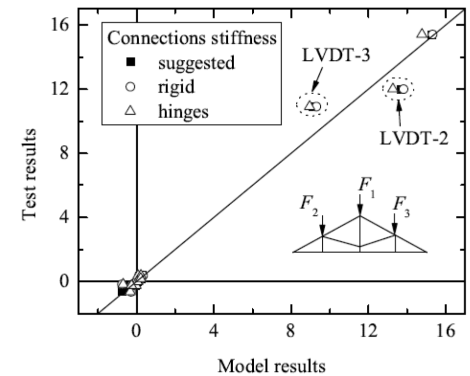


Optimization of Design for Floors, Roofs and Vaults

Analyses on roofs

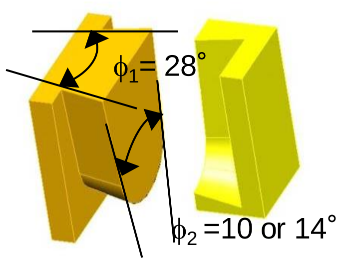
- Investigation on wooden trusses: loading tests, degradation assessment and analyses on joints allowed to validate reliable in-situ evaluations
- Numerical calibration allowed to consider different stiffness for joints (thus simulating deterioration and/or interventions)
- Modelling of series of strusses allowed to identify the influence of dimension and material used for the shared bearings
- Modeling of joints allowed to calibrate the mortise-tenon behaviour

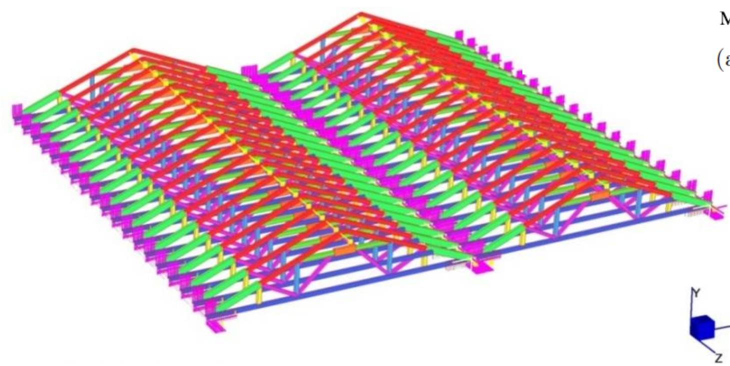




(a) 3F-C

$$F = 15\ln(s+1)\frac{100}{95+s}$$





Conclusions

- The optimization of horizontal components as floors, vaults and roofs in existing construction pursues a proper balance of technological advancement and preservation requirements.

- Traditional intervention solutions and materials need to be revaluated as they still show high performance also in comparison with modern/innovative materials, as composites (FRP, SRP, etc.).

- This is particularly relevant for the strengthening of floors, where double planking resulting in the best improvement of in-plane stiffness and displacement capacity of floors.

- As for vaults, composite strips have a definite advantage due to their high versatility and easy application; nevertheless, the use of selected mortar as matrix would guarantee more compatibility, durability and removability than epoxy resins, still improving both load and displacement capacity properly for a historical construction.

THANK YOU FOR YOUR KIND ATTENTION

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